

## Trends in Northern Hemisphere Surface Cyclone Frequency and Intensity

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### ABSTRACT

One of the hypothesized effects of global warming from increasing concentrations of greenhouse gases is a change in the frequency and/or intensity of extratropical cyclones. In this study, winter frequencies and intensities of extratropical cyclones in the Northern Hemisphere for the period 1959–97 are examined to determine if identifiable trends are occurring. Results indicate a statistically significant decrease in midlatitude cyclone frequency and a significant increase in high-latitude cyclone frequency. In addition, storm intensity has increased in both the high and midlatitudes. The changes in storm frequency correlate with changes in winter Northern Hemisphere temperature and support hypotheses that global warming may result in a northward shift of storm tracks in the Northern Hemisphere.

### 1. Introduction

Variations in extratropical cyclone frequency and intensity have a direct influence on surface climate through effects on cloud cover, winds, and precipitation frequency, duration, and magnitude. Thus, the frequencies and characteristics of cyclones (as well as anticyclones) have been examined by a number of studies (e.g., Colucci 1976; Sanders and Gyakum 1980; Parker et al. 1989; Agee 1991; Serreze et al. 1997; Key and Chan 1999). Assessments of changes in cyclone activity that may result from global warming are important for understanding regional climate change, which, in turn, is necessary to evaluate impacts on ecological systems, socioeconomic sectors (including agriculture, fisheries, water resources, and human settlements), and human health (Watson et al. 1998).

A number of studies have assessed the effect of global warming on cyclone activity through sensitivity experiments with general circulation models (GCMs). Using simulations of doubled- $\text{CO}_2$  climatic conditions from the Canadian Centre for Climate Modeling and Analysis GCM, Lambert (1995) found a significant reduction in the total number of cyclones in both hemispheres, but an increased frequency of intense cyclones, most pronounced in the Northern Hemisphere. However, storm

tracks showed little change in position. Lambert (1995) showed the reduction in cyclones as consistent with a reduction in baroclinicity in the lower troposphere in a warmed climate. In a simulation of future climatic conditions using the European Centre for Medium-Range Weather Forecasts (ECMWF) Hamburg GCM, that included gradually increasing atmospheric  $\text{CO}_2$ , Konig et al. (1993) also found a slight reduction in cyclone frequency for doubled- $\text{CO}_2$  climate conditions. However, contrasting with Lambert (1995), Konig et al. also identified a poleward shift in cyclone activity over the North Atlantic Ocean during autumn and winter, with a similar tendency over extended areas of the Southern Hemisphere. In addition, over the North Pacific Ocean, an eastward displacement of cyclone activity was noted, especially for winter and spring. Other modeling studies have examined regional (e.g., over the Atlantic and Pacific Oceans and North America) changes in storm tracks and cyclone frequencies associated with potential global warming (Held 1993; Stephenson and Held 1993; Hall et al. 1994; Watson et al. 1998).

These investigations point to considerable uncertainty in the response of both storm track locations and cyclone frequencies to global warming. As discussed by Held (1993) the issue is complex. While on the one hand, weakening of low-level baroclinicity in midlatitudes may lead to a weakening of storm tracks, it may be possible for some systems to draw on the increased supply of energy represented by strengthening of the baroclinicity aloft. The response of midlatitude eddies

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is also strongly influenced by increased levels of atmospheric moisture expected in a warmer climate. One effect is a direct enhancement of eddy energy through the additional release of latent heat [this mechanism was invoked by Hall et al. (1994) to explain the intensification of the Atlantic storm track in a warmed climate]. However, a competing effect exists in that when the atmosphere becomes moister, horizontal latent heat transport increases, meaning the eddies are more efficient in transporting energy poleward (Held 1993). Since smaller eddies are required to maintain the same temperature gradient, one may anticipate that eddy amplitudes will decrease as temperatures increase. These effects are relevant to changes in storm activity in a zonal mean sense.

Zonal asymmetries in storm track locations introduce additional complexities. Depressions tend to be organized into two primary tracks (Atlantic and Pacific). These tracks can be altered by regional changes in the mean stationary wave pattern in a warmed climate, as well as regional differences in continental versus oceanic warming (Stephenson and Held 1993). These changes are depicted differently in various GCMs. Furthermore, the relationship between regional baroclinicity and storm activity is not completely linear. For example, in an observational study of storm activity in the Northern Hemisphere, Nakamura (1992) demonstrated that baroclinic wave activity is actually suppressed in the Pacific basin during winter when the low-level regional baroclinicity and the strength of the Pacific jet is maximized. While the exact mechanisms are not clear, Nakamura (1992) shows that in a statistical sense, baroclinic wave activity in the Pacific is limited when the Pacific jet exceeds  $45 \text{ m s}^{-1}$ , as is common in midwinter. This midwinter suppression of baroclinic wave activity is not evident in the Atlantic basin, where the strength of the jet rarely exceeds  $45 \text{ m s}^{-1}$ .

Given the large differences between GCM predictions of storm activity under global warming, it is warranted to examine the extent to which changes have occurred within the period of instrumental records. Agee (1991) studied trends in the annual frequency of surface cyclones and anticyclones for the Northern Hemisphere, and their relationships with temperature. Agee found that in the Northern Hemisphere, warming and cooling trends are accompanied, respectively, by increases and decreases in both cyclone and anticyclone frequencies. These results are at odds with those modeling studies that indicate that warming will be associated with decreased cyclone activity in the midlatitudes. In a more recent study, Serreze et al. (1997) examined trends in winter (Oct–Mar) cyclone frequencies for the midlatitudes ( $30^{\circ}$ – $60^{\circ}\text{N}$ ) and the high latitudes ( $60^{\circ}$ – $90^{\circ}\text{N}$ ) of the Northern Hemisphere. They found that for the study period 1966–93 high-latitude cyclone frequencies increased and midlatitude cyclone frequencies decreased.

Serreze et al. (1997) did not compute correlations between winter cyclone frequencies and Northern Hemisphere

winter temperatures. However, their results suggest an inverse relation between midlatitude cyclone frequency and winter Northern Hemisphere temperatures (which have been increasing), and a positive relation between high-latitude cyclone frequencies and winter Northern Hemisphere temperatures. This is contrary to the results reported by Agee (1991). The differences between these two studies may be due to 1) the regions analyzed (Serreze et al. divided their analysis of the Northern Hemisphere into midlatitude and high-latitude cyclone frequencies) and 2) the method of computing the number of cyclones during a season.

Key and Chan (1999) examined trends in both 1000- (surface) and 500-hPa cyclone frequencies for the Northern and Southern Hemispheres for the period 1958–97. They found that for winter months (Dec–Feb), both the 1000- and 500-hPa cyclone frequencies in the midlatitudes of the Northern Hemisphere decreased, whereas cyclone frequencies for the high latitudes of the Northern Hemisphere increased. However, for spring, summer, and autumn, Key and Chan found opposite trends in 1000-hPa and 500-hPa cyclone frequencies for both the mid- and high latitudes of the Northern Hemisphere.

In summary, there is considerable uncertainty as to how cyclone activity will change in a warmed climate. The purpose of this study is to examine observed secular changes and trends in cyclone frequency and intensity in the Northern Hemisphere, and assess relationships between those changes and variations in Northern Hemisphere temperature.

## 2. Data and methods

The cyclone data used in this study were obtained from a 39-yr (1959–97) record of 6-hourly cyclone statistics for the Northern Hemisphere. The detection algorithm is essentially that described by Serreze (1995) and Serreze et al. (1997) except it has been modified for application to the more temporally consistent sea level pressure (SLP) fields from the National Centers for Environmental Prediction–National Center for Atmospheric Research (NCEP–NCAR) reanalysis project (Kalnay et al. 1996). Cyclone detection relies on the identification of gridpoint SLP values surrounded by gridpoint values at least 1 hPa higher than the central point being tested. Intensity is based on the local Laplacian of pressure at each cyclone center. For this study, only cyclones that existed for two or more consecutive observation periods (i.e., at least 12 h) were used. In addition, we focus on the winter season (Nov–Mar) for which Northern Hemisphere temperature trends have been largest. Winter Northern Hemisphere temperature data for the years 1959–97 were obtained from the Jones et al. (1999) dataset (available online at <http://cdiac.esd.ornl.gov/ftp/trends/temp/jonescru/global.dat>).

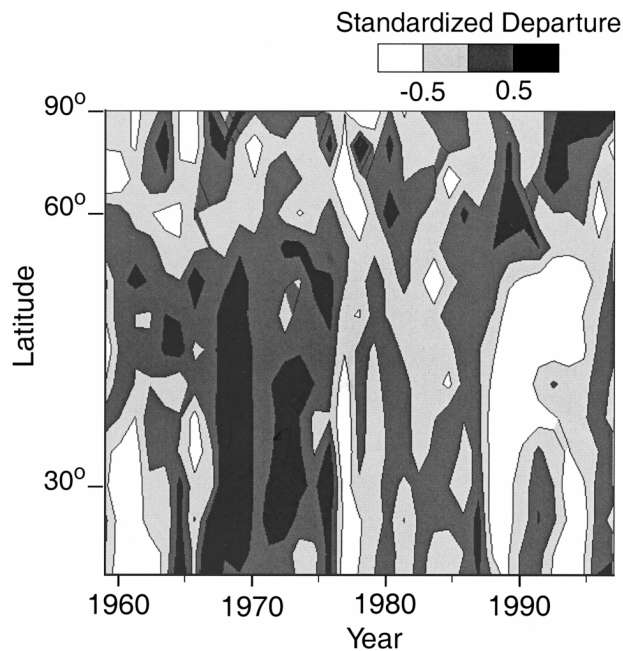


FIG. 1. Standardized departures of winter (Nov–Mar) cyclone counts for  $5^\circ$  latitudinal bands in the Northern Hemisphere, 1959–97.

### 3. Results and discussion

#### a. Trends in cyclone frequency

Figure 1 illustrates cyclone counts for  $5^\circ$  latitudinal bands (expressed as standardized departures and illustrated on an equal area basis). The standardized departures ( $z$  scores) were computed for each  $5^\circ$  latitudinal band by subtracting the respective 1959–97 mean from each value and dividing by the respective 1959–97 standard deviation. The standardized departures indicate a decrease with time in cyclone frequency for the region between  $30^\circ$  and  $60^\circ\text{N}$  and an increase in cyclone frequency for the region poleward of  $60^\circ\text{N}$ .

Following the approach used by Serreze et al. (1997), the standardized departures of cyclone counts were averaged for the  $30^\circ$ – $60^\circ\text{N}$  (midlatitude) and  $60^\circ$ – $90^\circ\text{N}$  (high latitude) bands. The data were subdivided into these groups because previous studies (i.e., Serreze et al. 1997; Key and Chan 1999) found significant differences in cyclone characteristics for these latitudinal bands. Application of linear regression (and accounting for the effects of lag-1 correlation in the cyclone frequency time series on the effective number of observations) indicates a statistically significant increase in high-latitude winter cyclone frequency with time (Fig. 2a, correlation with time is 0.37, significant at a 95% confidence level), and a statistically significant decrease in midlatitude winter cyclone frequency (Fig. 2b, correlation with time is  $-0.50$ , significant at a 90% confidence level). These results are similar to those reported by Serreze et al. (1997). An obvious caveat is that the

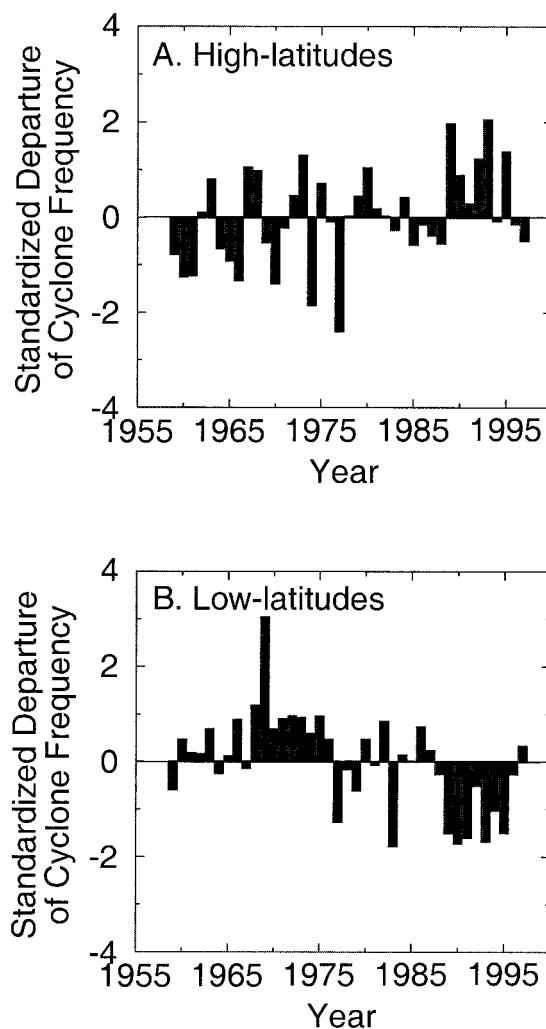


FIG. 2. Standardized departures of winter (Nov–Mar) cyclone counts in the Northern Hemisphere, 1959–97, for (a) high latitudes ( $60^\circ$ – $90^\circ\text{N}$ ), and (b) midlatitudes ( $30^\circ$ – $60^\circ\text{N}$ ).

observed increase in high-latitude cyclone frequency may be due, in part, to improvements in the quantity and quality of assimilation data with time. However, it is unlikely that improved observations can account for the simultaneous decrease in midlatitude cyclone frequency.

In examining these time series more closely, it is apparent that the trends, especially for the midlatitudes, reflect a regime shift during the mid-1970s (Trenberth 1990). This corresponds to the mid-1970s climate transition noted in other studies. Miller et al. (1993) identified an abrupt shift in the basic state of the atmosphere–ocean climate system over the North Pacific Ocean during the 1976–77 winter season. This was associated with a pronounced change in storm tracks across a large part of the Northern Hemisphere (Folland and Parker 1990; Trenberth 1990; McCabe et al. 2000).

Another interesting feature in Figs. 2a and 2b is a pronounced increase in cyclone frequency in high lat-

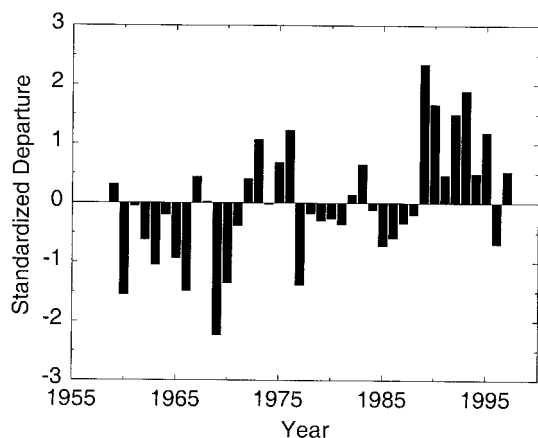


FIG. 3. Standardized departures of the mean winter (Nov–Mar) AO index, 1959–97.

itudes and a pronounced decrease in midlatitudes around 1989. These changes occur coincident with a significant change in the Arctic oscillation (AO) index (Fig. 3). The AO is defined as the leading empirical orthogonal function of Northern Hemisphere area-weighted sea level pressure anomalies poleward of  $20^{\circ}\text{N}$  (Thompson and Wallace 1998). The positive polarity of the AO can be interpreted as a strengthening and shrinking of the polar vortex. The North Atlantic oscillation (NAO) represents the primary component of the AO. During positive AO conditions cyclone activity in the Northern Hemisphere shifts poleward (Serreze et al. 1997; Clark et al. 1999). When the AO is negative, the polar vortex is in a weakened state and cyclone activity shifts south. The correlations between the AO and the time series of high-latitude and midlatitude cyclone frequencies are 0.69 and  $-0.56$ , respectively, both statistically significant at the 95% confidence level. The changes in cyclone distributions seen here also are consistent with previous studies illustrating recent decreases in SLP over the Arctic with compensating pressure increases over the midlatitudes (Walsh et al. 1996; Serreze et al. 1997, 2000). Hurrell (1996) suggests that almost 50% of the winter (Dec–Mar) temperature variance over the Northern Hemisphere (north of  $20^{\circ}\text{N}$ ) since 1935 is due to the combined effects of variability in atmospheric circulation forced by the NAO (a component of the AO) and the Southern Oscillation. Thompson et al. (2000) subsequently show that over the period 1968–97 approximately half of the observed winter warming over Siberia and all of the winter cooling over eastern Canada and Greenland is linearly congruent with the monthly time series of the AO.

Another important mode of global climate variability is the El Niño–Southern Oscillation (ENSO; Kiladis and Diaz 1989). Some studies have suggested a relation between ENSO and global warming (Trenberth and Hoar 1996, 1997). One index of ENSO is the sea surface temperature (SST) anomaly in the Niño-3.4 region. The

Niño-3.4 region encompasses the area  $5^{\circ}\text{S}$ – $5^{\circ}\text{N}$ , and  $120^{\circ}$ – $170^{\circ}\text{W}$ . Positive (negative) Niño-3.4 SST anomalies correspond to El Niño (La Niña) conditions. Winter (Nov–Mar) Niño-3.4 SST values were averaged to compute a time series for the years 1959–97. Correlations between the Niño-3.4 time series and cyclone frequencies for the high and midlatitudes are not found to be significant (0.01 and  $-0.18$ , respectively).

The conclusion that anthropogenic greenhouse warming has been a primary driver of changes in northern high-latitude climate must be treated cautiously (Serreze et al. 2000). Although climate models and observations generally agree in terms of changes in Arctic temperatures and atmospheric circulation, there are some discrepancies. For example, models generally estimate the strongest Arctic warming to occur during autumn and winter, whereas observations indicate the greatest warming during winter and spring (Kattenberg et al. 1996; Serreze et al. 2000).

#### b. Trends in cyclone intensity

For both the high latitudes and the midlatitudes, cyclone intensity has increased over the 1959–97 period (Figs. 4a and 4b). The linear trend (accounting for lag-1 correlations in the intensity time series) for high latitudes ( $r = 0.53$ , significant at a 99% confidence level) is much stronger than that for midlatitudes ( $r = 0.39$ , significant at a 90% confidence level). In addition, high-latitude cyclone intensity exhibits a pronounced increase around 1989 similar to the change observed in cyclone frequency, and coincident with the increase in the AO index. Again, these results must be viewed with recognition that the assimilation database available for the NCEP–NCAR reanalysis has improved through time.

#### c. Relations with Northern Hemisphere temperature

Time series of winter cyclone frequency and intensity were correlated with the time series of mean Northern Hemisphere winter temperature. Results indicate statistically significant correlations for both the high and midlatitudes (Table 1, Figs. 5a and 5b). The correlation between winter temperature and cyclone frequency for the midlatitudes ( $r = -0.58$ ) is much stronger than that for the high latitudes ( $r = 0.38$ ). The negative correlation between midlatitude cyclone frequency and winter temperature, and the positive correlation between high-latitude cyclone frequency and winter temperature lend support to the idea that global warming may result in increased cyclone activity in high latitudes and decreased cyclone activity in midlatitudes (Held 1993; Stephenson and Held 1993; Konig et al. 1993; Hall et al. 1994; Lambert 1995). In contrast to the results for cyclone frequency, the correlations between winter temperature and cyclone intensity are small and are not significant for either latitudinal band (Table 1).

One interpretation of these results is that increasing

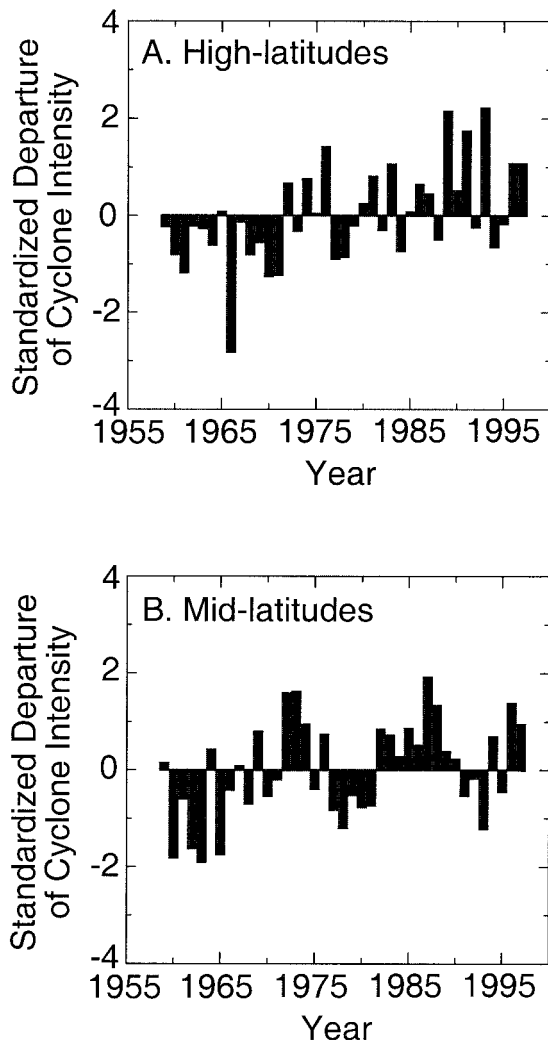


FIG. 4. Standardized departures of winter (Nov–Mar) cyclone intensity in the Northern Hemisphere, 1959–97, for (a) high latitudes ( $60^{\circ}$ – $90^{\circ}$ N), and (b) midlatitudes ( $30^{\circ}$ – $60^{\circ}$ N).

levels of atmospheric  $\text{CO}_2$  have forced increases in Northern Hemisphere temperature, which in turn force changes in circulation and cyclone activity. This interpretation is consistent with model sensitivity studies. However, a more straightforward interpretation is that cyclone activity and temperature simply covary on interannual timescales, and the trends we see are not related to greenhouse forcing in any way. In this context, recall from section 3a that interannual variations in Northern Hemisphere temperature may themselves be forced by interannual variations in the dominant modes of low-frequency atmospheric variability (Hurrell 1996; Thompson et al. 2000; Serreze et al. 2000). In this observational study we cannot objectively determine which of these opposing interpretations is true. Our intent in presenting these changes in cyclone activity and temperature is to provide a more complete picture of observed changes in the climate system.

TABLE 1. Correlations between mean Northern Hemisphere winter temperature and winter cyclone frequency and intensity for the high latitudes ( $60^{\circ}$ – $90^{\circ}$ N) and the midlatitudes ( $30^{\circ}$ – $60^{\circ}$ N).

Cyclone characteristic	Correlation with winter temperature
High-latitude cyclone frequency	0.38*
Midlatitude cyclone frequency	–0.58**
High-latitude cyclone intensity	0.25
Midlatitude cyclone intensity	–0.13

\* Significant at a 95% confidence level.

\*\* Significant at a 99% confidence level.

#### 4. Conclusions

This study shows that for the Northern Hemisphere, winter cyclone frequency has increased in high latitudes and has decreased in midlatitudes. However, for both latitudinal bands, winter cyclone intensity has increased. The changes in cyclone frequency correspond to sig-

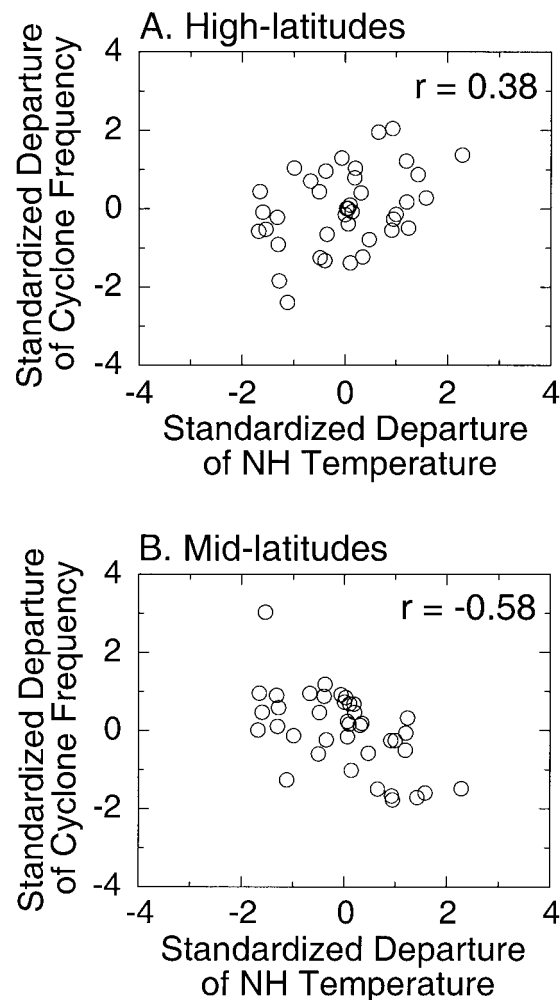


FIG. 5. Comparisons of standardized departures of mean Northern Hemisphere winter (Nov–Mar) temperature and (a) high latitude ( $60^{\circ}$ – $90^{\circ}$ N) cyclone frequency, and (b) midlatitude ( $30^{\circ}$ – $60^{\circ}$ N) cyclone frequency (1959–97).

nificant climate transitions: the mid-1970s climate transition and the 1989 shift in the AO index. Winter cyclone frequency is significantly correlated with Northern Hemisphere winter temperatures. Variability in winter cyclone intensity is not significantly correlated with Northern Hemisphere temperatures. These results provide some support for climate modeling studies (e.g., Konig et al. 1993) suggesting that global warming may be associated with an increase in high-latitude cyclone frequency and a decrease in midlatitude cyclone frequency.

## REFERENCES

- Agee, E. M., 1991: Trends in cyclone and anticyclone frequency and comparison with periods of warming and cooling over the Northern Hemisphere. *J. Climate*, **4**, 263–267.
- Clark, M. P., M. C. Serreze, and D. A. Robinson, 1999: Atmospheric controls on Eurasian snow extent. *Int. J. Climatol.*, **19**, 27–40.
- Colucci, S. J., 1976: Winter cyclone frequencies over the eastern United States and adjacent western Atlantic, 1964–1973. *Bull. Amer. Meteor. Soc.*, **57**, 548–553.
- Folland, C. K., and D. E. Parker, 1990: Observed variations of sea surface temperature. *Climate–Ocean Interaction*, M. E. Schlesinger, Ed., Kluwer, 21–52.
- Hall, N. M. J., B. J. Hoskins, P. J. Valdes, and C. A. Senior, 1994: Storm tracks in a high-resolution GCM with doubled carbon dioxide. *Quart. J. Roy. Meteor. Soc.*, **120**, 1209–1230.
- Held, I. M., 1993: Large-scale dynamics and global warming. *Bull. Amer. Meteor. Soc.*, **74**, 228–241.
- Hurrell, J. W., 1996: Influence of variations in extratropical wintertime teleconnections on Northern Hemisphere temperatures. *Geophys. Res. Lett.*, **23**, 665–668.
- Jones, P. D., T. J. Osborn, K. R. Briffa, and D. E. Parker, 1999: Global monthly and annual temperature anomalies (degrees C), 1856–1998. Climatic Research Unit, School of Environmental Sciences, University of East Anglia, Norwich, United Kingdom. [Available online at <http://cdiac.esd.ornl.gov/ftp/trends/temp/jonescru/global.dat>.]
- Kalnay, E., and Coauthors, 1996: The NCEP/NCAR 40-Year Reanalysis Project. *Bull. Amer. Meteor. Soc.*, **77**, 437–471.
- Kattenberg, A., and Coauthors, 1996: Climate Models: Projections of future climate. *Climate Change 1995: The Science of Climate Change, Contribution of Working Group I to the Second Assessment of the Intergovernmental Panel on Climate Change*, J. T. Houghton et al., Eds., Cambridge University Press, 289–357.
- Key, J. R., and A. C. K. Chan, 1999: Multidecadal global and regional trends in 1000 mb and 500 mb cyclone frequencies. *Geophys. Res. Lett.*, **26**, 2053–2056.
- Kiladis, G. N., and H. F. Diaz, 1989: Global climatic anomalies associated with extremes of the Southern Oscillation. *J. Climate*, **2**, 1029–1090.
- Konig, W., R. Sausen, and F. Sielmann, 1993: Objective identification of cyclones in GCM simulations. *J. Climate*, **6**, 2217–2231.
- Lambert, S. J., 1995: The effect of enhanced greenhouse warming on winter cyclone frequencies and strengths. *J. Climate*, **8**, 1447–1452.
- McCabe, G. J., A. G. Fountain, and M. Dyurgerov, 2000: Variability in winter mass balance of Northern Hemisphere glaciers and relations with atmospheric circulation. *Arct. Antarct. Alp. Res.*, **32**, 64–72.
- Miller, A. J., D. R. Cayan, T. P. Barnett, N. E. Graham, and J. M. Oberhuber, 1993: The 1976–77 climate shift of the Pacific Ocean. *Oceanography*, **7**, 21–26.
- Nakamura, H., 1992: Midwinter suppression of baroclinic wave activity in the Pacific. *J. Atmos. Sci.*, **49**, 1629–1642.
- Parker, S. S., J. T. Hawes, S. J. Colucci, and B. P. Hayden, 1989: Climatology of 500-mb cyclones and anticyclones, 1950–85. *Mon. Wea. Rev.*, **117**, 558–570.
- Sanders, F., and R. Gyakum, 1980: The synoptic-dynamic climatology of the Bomb. *Mon. Wea. Rev.*, **108**, 1589–1606.
- Serreze, M. C., 1995: Climatological aspects of cyclone development and decay in the Arctic. *Atmos.–Ocean*, **33**, 1–23.
- , F. Carse, R. G. Barry, and J. C. Rogers, 1997: Icelandic low cyclone activity: Climatological features, linkages with the NAO and relationships with recent changes in the Northern Hemisphere circulation. *J. Climate*, **10**, 453–464.
- , and Coauthors, 2000: Observational evidence of recent change in the northern high-latitude environment. *Climatic Change*, **46**, 159–207.
- Stephenson, D. B., and I. M. Held, 1993: GCM response of Northern winter stationary waves and storm tracks to increasing amounts of carbon dioxide. *J. Climate*, **6**, 1859–1870.
- Thompson, D. W. J., and J. M. Wallace, 1998: The Arctic Oscillation signature in the wintertime geopotential height and temperature fields. *Geophys. Res. Lett.*, **25**, 1297–1300.
- , —, and G. C. Hegerl, 2000: Annular models in the extratropical circulation. Part II: Trends. *J. Climate*, **13**, 1018–1036.
- Trenberth, K. E., 1990: Recent observed interdecadal climate changes in the Northern Hemisphere. *Bull. Amer. Meteor. Soc.*, **71**, 988–993.
- , and T. J. Hoar, 1996: The 1990–1995 El Niño–Southern Oscillation event: Longest on record. *Geophys. Res. Lett.*, **23**, 57–60.
- , and —, 1997: El Niño and climate change. *Geophys. Res. Lett.*, **24**, 3057–3060.
- Walsh, J. E., W. L. Chapman, and T. L. Shy, 1996: Recent decrease of sea level pressure in the central Arctic. *J. Climate*, **9**, 480–486.
- Watson, R. T., M. C. Zinyowera, and R. H. Moss, 1998: The regional impacts of climate change: An assessment of vulnerability. A Special Report of IPCC Working Group II, Cambridge University Press, 517 pp.